



Optimal policies for climate change: A joint consideration of CO₂ and methane

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HIGHLIGHTS

- This paper studies the optimal policies under joint accounting of CO₂ and methane.
- A dynamic model is theoretically developed and calibrated to the global warming case.
- Different policies are solved under asymmetric information and pollutant correlation.
- It is optimal to levy tax on both CO₂ and methane.
- A mixed policy with tax on CO₂ and quota on methane is the second-ranked choice.

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ABSTRACT

Climate change mitigation requires the reduction of greenhouse gas (GHG) emissions. The majority of the discussions on climate change policy focus exclusively on the reduction of carbon dioxide (CO₂) emissions but ignore other important GHGs such as methane. This paper investigates the optimal choice of policy instruments under the joint consideration of CO₂ and methane in a dynamic setting with asymmetric information and pollutant correlations. We develop a dynamic programming model with two state variables and calibrate it to the global warming case. The results show that it is optimal to levy tax on both CO₂ and methane. A mixed strategy that implements a tax on CO₂ and a quota on methane is the second-ranked choice.

1. Introduction

Climate change has been raising concerns globally since the Kyoto Protocol was signed in the 1990s. Although governments, agencies and the public all agree on the necessity to control, mitigate and adapt to climate change, no consensus is gained on the regulating policy choices. Theoretically, intensive discussions exist on the price (tax) versus quantity (quota) comparison, see e.g. Weitzman [1], Pizer [2], Endres and Finus [3], and Karp and Zhang [4]. In practice, the public also debates on the policy options. For instance, the US Vice President Al Gore advocates carbon tax, while the UK Environment Secretary David Miliband proposes an alternative system including both individual carbon quotas and a national quota to be allocated or sold to industries.

The majority of the discussions on climate policy design focus on the emission reduction of carbon dioxide (CO₂) [5,6], the most important GHG. However, CO₂ is not the only cause of climate change. Methane,

which contributes 18% of the total expected global warming [7], is also one of the most important GHGs. Shindell et al. [8] point out that both the CO₂ and methane are with the most radiative forcing associated with human activity. In addition, methane is an extremely potent greenhouse gas with 25 times the warming potential of carbon dioxide over a 100-year time period. As stated in Michaelis [9], policy measures against global warming should tackle not only the emissions of carbon dioxide, but also the emissions of methane and others.

Taking methane into consideration, the interaction of multiple GHGs in joint production, or abatement process should not be neglected. The correlation effect can be either substitutive or complementary [10]. For instance, carbon capture and storage could reduce methane with the pre-combustion technology, making the two pollutants substitutes in this case. The synergies and tradeoffs between pollutants cause different environmental policies correlated, which further emphasize the need for policy coordination [11]. Hence,

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ignoring the other pollutant methane as well as the interaction between GHGs, and implementing CO₂ policy independently will hardly ensure efficiency in climate change mitigation.

Another challenge in designing climate policy is the considerable uncertainty about the cost of reducing emissions [12]. The cost uncertainty arises partly due to the uncertainty about the level of future baseline emissions [2]. Weitzman [1] shows that uncertainty (asymmetric information) in costs leads to a potentially significant efficiency distinction between otherwise equivalent price (tax) and quantity (quota) regulations in pollution control. Though this well-established result is important guidance for the optimal instruments in climate change control and has valuable policy implications (see the discussions in e.g., Tol [13]), it is constrained with one pollutant and in a static setting, i.e., pollution does not accumulate over time. However, this is not the case in climate change due to atmospheric concentration of GHGs [14]. The damage of GHGs depends not on the flow of emissions in a single year as airborne particulate matter or volatile organic compounds, but on the accumulated stock of emissions which persists for decades. Correspondingly, the Kyoto Protocol and Framework Convention on Climate Change set a upper limit of emissions on the atmospheric stock of GHGs [15].

As more than one pollutant exist, and the danger of global warming depends on the stocks [16], the policy analysis on climate change requires multiple-pollutant modeling in a dynamic setting. However, previous literature focuses either on a single stock pollutant (e.g., [14]) or on multiple flow pollutants (e.g., [17]) in the price-versus-quantity policy debates. To fill in the gap, this paper uses a stochastic dynamic framework with multiple GHGs (CO₂ and methane) to investigate the optimal policy instruments (taxes versus quotas) against global warming, under asymmetric information and pollutant correlations.

We build a dynamic model consisting of a representative firm and a regulator, facing two stock pollutants with correlations in the abatement process. We derive the theoretical solutions under different price-and-quantity policy combinations, and calibrate the model to the climate change case. The simulations yield the results under different policy schemes, among which the policy of taxing both carbon dioxide and methane dominates other policy choices with the lowest total social cost. In addition, a mixed policy that implements a tax on carbon dioxide and a quota on methane is always the second-ranked policy option.

The rest of the paper is organized as follows. The next section reviews previous studies in the literature. Section 3 describes the general model and derives the solutions under different policy instruments. Section 4 calibrates the model to the climate change case and Section 5 presents the results and discussions. Finally, Section 6 concludes the paper and highlights the policy implications of the results. Some technical details are relegated to appendix.

2. Literature review

Previous literature has acknowledged the prevalence of both the tax and quota policies [18]. A number of studies investigate the effect of carbon tax [19–21] and quota [5,22,23] in climate change mitigation, respectively. The literature on price-versus-quota policy comparison starts with Weitzman [1] who utilizes a static framework. To account for the stock externality of GHG emissions in climate change, following studies have employed the dynamic setting. For instance, Hoel and Karp [16,14] and Pizer [2] conclude that taxes dominate quotas for the control of CO₂ in a dynamic program model and in an integrated climate economy model, respectively. Newell and Pizer [15] account for the serial correlation of cost shocks and find that a price-based instrument generates several times the expected net benefits of a quantity instrument. All above mentioned literature confirms the dominance of emission taxes over quotas, however historical evidence suggests that command and control type of regulations are still predominant instruments worldwide due to different enforceability capacities [24]. Endres

and Finus [3] show that an agreement under cost-inefficient quota regime may be superior to an efficient tax agreement with respect to ecological and welfare criteria. Karp and Zhang [4] also recognize the advantage of quotas over emission taxes where investment policy is information-constrained efficient with the use of quotas. In Chiu et al. [25], they find that the economic effects of taxes and quotas on energy prices are uncertain, which depend on market structures. All these studies focus on a single pollutant - CO₂, the most important GHG.

The literature on multiple pollutants emphasizes the interaction between them [26] and how the joint accounting of multiple pollutants affects the policy makings. Caplan and Silva [27] explore efficient mechanism to control correlated externalities. Silva and Zhu [28] find double dividends in a multi-pollutant setting, and Ambec and Coria [29] analyze the interplay of environmental policies with multiple pollutants. Fullerton and Karney [30] also study policy interactions (suboptimal tax or permit policy) when polluting inputs can be substitutes or complements. On the choice of policy instruments for multiple pollutants, Ambec and Coria [17] investigate how multi-pollutant interactions in abatement efforts influence the optimal policies with two flow pollutants. Meunier [31] analyzes the effect of a second unregulated externality on the price- quantity choice, involving interactions in demand system and the external cost. However, previous studies on the tax or quota regulation for multiple pollutants appear in a static setting only.

Regarding multiple pollutants in a dynamic framework with stock pollutants, the existing research does not focus on the choice of policy instruments. For example, Michaelis [9] calculates a scenario of efficient charge system with a dynamic optimization model. Moslener and Requate [32] analyze the optimal path of abatement in dynamic multi-pollutant problems, and characterize it to the greenhouse problem in Moslener and Requate [33]. Kuosman and Laukkanen [34] study both flow and stock pollutants, and show that the optimal policy is often a corner solution, in which abatement should be focused on a single pollutant. Yang and Menon [35] also study climate change mitigation with correlated pollutants using a regional dynamic general-equilibrium model. Unlike in this paper, there is no uncertainty (asymmetric information) in their studies, which implies the equivalence of price and quantity regulations.

Though previous research has important implications in environmental regulation, the findings based on a single stock pollutant [2,14,15] or multiple flow pollutants [17] may not be fully applicable to climate change problem. Therefore, the contribution of this paper lies in two folds. On the one hand, this study is the first attempt to theoretically accommodate multiple pollutants (as well as their correlations) and a dynamic framework (with asymmetric information) in the price-versus-quantity policy debates. On the other hand, with a more realistic setting and calibrated simulation in this study, the policy implications on optimal regulatory instruments of multiple GHGs can be well applicable to global climate change issue.

3. The model

3.1. Elements of the model

In each time period t , a representative firm is emitting two pollutants: pollutant 1 (e.g., CO₂) and pollutant 2 (e.g., methane). The total abatement cost for the firm is:

$$C(E_1(t), E_2(t), \theta(t)) = \frac{m_1}{2}(\bar{E}_1 - E_1(t))^2 + \frac{m_2}{2}(\bar{E}_2 - E_2(t))^2 + \omega(\bar{E}_1 - E_1(t))(\bar{E}_2 - E_2(t)) + \theta(t)[(\bar{E}_1 - E_1(t)) + (\bar{E}_2 - E_2(t))] \quad (1)$$

where \bar{E}_i presents the laissez-faire emission level of pollutant i ($i = 1, 2$) and $E_i(t)$ is the emission of pollutant i in period t . The parameters m_i ($i = 1, 2$) are positive and the parameter ω in the cost function reflects

the (dis) economies of scope in the joint abatement of the two pollutants. If $\omega < 0$, the cost of joint abatement is less than the cost of abating each pollutant separately, implying the existence of economies of scope. The pollutants are referred as complements, consistent with Ambec and Coria [17]. In contrast, $\omega > 0$ implies that diseconomies of scope exist in joint abatement and the pollutants are substitutes. The parameters ω and m_i are common knowledge, while $\theta(t)$ is private information (shocks) in the abatement cost that is not known by the regulators. We assume that the random variable $\theta(t)$ is independently and identically distributed (i.i.d.) with mean 0 and variance σ^2 , which implies that the possible serial correlation in the cost shocks is not considered as in Hoel and Karp [14].¹ Consistent with Moslener and Requate [32], we assume $m_1 m_2 - \omega^2 > 0$ to assure the convexity of the abatement cost function.

The accumulated stock of pollutant i at the beginning of period t is denoted as $S_i(t)$ and the dynamics of pollutant stocks can be written as:

$$S_i(t+1) = (1-\rho_i)S_i(t) + E_i(t), S_i(0) = S_i^0 \geq 0 \quad (2)$$

where ρ_i is the stock decay rate of pollutant i . The environmental damages of pollutants depend on the stocks of the pollutants and are assumed to be in a quadratic form [16,15]:

$$D(S_1, S_2) = d_1 S_1 + d_2 S_2 + \frac{\varepsilon_1}{2} [S_1]^2 + \frac{\varepsilon_2}{2} [S_2]^2 + \varpi S_1 S_2 \quad (3)$$

where d_i and ε_i are the damage coefficients on the linear and quadratic term for pollutant i , respectively. As can be seen in (3), we also include the interactions between pollutants into environmental damages, which is reflected in the parameter ϖ . If $\varpi = 0$, the damages of the two pollutants are additively separable. That is, the environmental damage caused by one additional unit of pollutant i is not affected by pollutant j ($j \neq i$). If $\varpi < 0$, the environmental damage caused by emission of pollutant i is reduced by existence of pollutant j (countervailing interactions). In contrast, $\varpi > 0$ implies that the environmental damage of pollutant i is aggravated by pollutant j due to synergistic interactions. We further assume $\varepsilon_i > 0$ and $\varepsilon_1 \varepsilon_2 - \varpi^2 > 0$ to ensure the convexity of the damage function.²

With a discount factor δ and initial values of the stocks S_i^0 , the regulator minimizes the expected present discounted value of social costs:

$$V(S_1^0, S_2^0, k) = \min_{E_{\theta(t)}} \sum_{t=0}^{\infty} \delta^t [C(E_1(t), E_2(t), \theta(t)) + D(S_1(t), S_2(t))] \quad (4)$$

subject to the dynamics of pollutant stocks (2) under the policy combination k . Possible combinations of instruments regulating the two stock pollutants are: quotas on both pollutants ($k = QQ$); taxes on both pollutants ($k = TT$); a quota on pollutant 1 and a tax on pollutant 2 ($k = QT$), and a tax on pollutant 1 with a quota on pollutant 2 ($k = TQ$). Recursively, one can rewrite the regulator's problem as:

$$V[S_1(t), S_2(t), k] = \min_{E_{\theta(t)}} \{C(E_1(t), E_2(t), \theta(t)) + D(S_1(t), S_2(t)) + \delta V[(1-\rho_1)S_1(t) + E_1(t), (1-\rho_2)S_2(t) + E_2(t), k]\} \quad (5)$$

where $V(S_1, S_2, k)$ is the value function of the regulator. We compare price and quantity regulatory instruments in the following section.

3.2. Solutions under different policy regimes

3.2.1. Quotas on both pollutants

For the quantity regulations, i.e., quotas, we assume that they are

¹ This assumption can facilitate a clear comparison with the results of Weitzman [1] and its following studies; see Hoel and Karp [14].

² These assumptions ensure the strict convexity of the damage function. Actually, the minimization problem of the regulator stated below requires that at least one of the two functions (abatement cost function and environmental damage function) should be strictly convex. Hence weakly convex damage function can also be allowed when the abatement cost is strictly convex.

always binding, as in Hoel and Karp [14], Ambec and Coria [17] for instance. That is, if the regulator sets the quotas for the two pollutants, the firm chooses to emit exactly the same amount of pollutants as required by the quotas. In this case, the dynamics of the pollutant stocks (2) are deterministic. In Appendix A.1, we show that the value function is quadratic in pollution stocks:

$$V(S_1, S_2, QQ) = \alpha + \beta_1 S_1 + \beta_2 S_2 + (\varphi_1/2)[S_1]^2 + (\varphi_2/2)[S_2]^2 + \gamma S_1 S_2 \quad (6)$$

and the optimal emission strategy for pollutant i follows:

$$E_i = \kappa_i - \eta_i S_1 - \mu_i S_2 \quad (7)$$

where the values of κ_i, η_i and μ_i ($i = 1, 2$) depend on the coefficients of the value function $V(S_1, S_2, QQ)$ and model parameters. The coefficients of this value function satisfy the following equations (see Appendix A.1):

$$\gamma = m_1 \eta_1 \mu_1 + m_2 \eta_2 \mu_2 + \omega(\eta_1 \eta_2 + \mu_1 \mu_2) + \varpi + \delta \varphi_1 [-(1-\rho_1-\eta_1)\mu_1] + \varphi_2 [-(1-\rho_2-\eta_2)\mu_2] + \gamma [(1-\rho_1-\eta_1)(1-\rho_2-\eta_2) + \mu_1 \mu_2] \quad (8.1)$$

$$\varphi_1 = m_1(\eta_1)^2 + m_2(\mu_2)^2 + 2\omega\eta_1\mu_2 + \varepsilon_1 + \delta\{\varphi_1(1-\rho_1-\eta_1)^2 + \varphi_2(\mu_2)^2 + \gamma[-2(1-\rho_1-\eta_1)\mu_2]\} \quad (8.2)$$

$$\varphi_2 = m_2(\eta_2)^2 + m_1(\mu_1)^2 + 2\omega\eta_2\mu_1 + \varepsilon_2 + \delta\{\varphi_2(1-\rho_2-\eta_2)^2 + \varphi_1(\mu_1)^2 + \gamma[-2(1-\rho_2-\eta_2)\mu_1]\} \quad (8.3)$$

$$\beta_1 = m_1(\bar{E}_1 - \kappa_1)\eta_1 + m_2(\bar{E}_2 - \kappa_2)\mu_2 + \omega[(\bar{E}_1 - \kappa_1)\mu_2 + (\bar{E}_2 - \kappa_2)\eta_1] + \theta(\eta_1 + \mu_2) + d_1 + \delta\{\beta_1(1-\rho_1-\eta_1) - \beta_2\mu_2 + \varphi_1\kappa_1(1-\rho_1-\eta_1) + \varphi_2[-\kappa_2\mu_2] + \gamma[\kappa_1\mu_2 + (1-\rho_1-\eta_1)\kappa_2]\} \quad (8.4)$$

$$\beta_2 = m_2(\bar{E}_2 - \kappa_2)\eta_2 + m_1(\bar{E}_1 - \kappa_1)\mu_1 + \omega[(\bar{E}_2 - \kappa_2)\mu_1 + (\bar{E}_1 - \kappa_1)\eta_2] + \theta(\eta_2 + \mu_1) + d_2 + \delta\{\beta_2(1-\rho_2-\eta_2) - \beta_1\mu_1 + \varphi_2\kappa_2(1-\rho_2-\eta_2) + \varphi_1[-\kappa_1\mu_1] + \gamma[\kappa_2\mu_1 + (1-\rho_2-\eta_2)\kappa_1]\} \quad (8.5)$$

$$\alpha = \frac{m_1}{2}(\bar{E}_1 - \kappa_1)^2 + \frac{m_2}{2}(\bar{E}_2 - \kappa_2)^2 + \omega(\bar{E}_1 - \kappa_1)(\bar{E}_2 - \kappa_2) + \delta\{\alpha + \beta_1\kappa_1 + \beta_2\kappa_2 + \frac{\varphi_1}{2}(\kappa_1)^2 + \frac{\varphi_2}{2}(\kappa_2)^2 + \gamma\kappa_1\kappa_2\} \quad (8.6)$$

Eqs. (8.1)–(8.6) constitute a system of nonlinear equations in $\gamma, \varphi_i, \beta_i$, and α (recall that κ_i, η_i and μ_i are functions of $\gamma, \varphi_i, \beta_i$; see Appendix A.1). Solving this system of equations would give the values of $\gamma, \varphi_i, \beta_i$, and α . For a restrictive symmetric case, an analytic solution can be obtained for both pollutants.³ However, the manipulation complexity precludes the general analytic solutions of (8.1)–(8.6). The case of asymmetric pollutants (e.g., CO₂ and methane) can only be solved with the assistance of numerical methods, which is shown in Section 5.

3.2.2. Taxes on both pollutants

Different from the case of quantity regulations, under which the representative firm simply emits the amount of pollution set by the quotas, under the price regulations (tax) the firm chooses emissions to solve the optimization problem. As in Hoel and Karp [14], we assume that the representative firm's emission decisions have no (appreciable) effect on aggregate emissions. Therefore, the firm takes aggregate emissions as exogenous and understands that it alone cannot affect future regulations. That is, the firm will behave non-strategically and take both the current and future policies as exogenous. Specifically, in each time period, the firm chooses emissions to solve the static optimization problem: $\min C(E_1, E_2, \theta) + \tau_1 E_1 + \tau_2 E_2^c$, taking the taxes τ_1 and τ_2 as given. The first order conditions yield the optimal emissions of the two pollutants under taxes: $E_1 = X_1 + \frac{(m_2 - \omega)\theta}{m_1 m_2 - \omega^2}$ and $E_2 = X_2 + \frac{(m_1 - \omega)\theta}{m_1 m_2 - \omega^2}$,

³ The detailed results are available from the author upon request.

where $X_1 = \bar{E}_1 - \frac{m_2 \tau_1 - \omega \tau_2}{m_1 m_2 - \omega^2}$ and $X_2 = \bar{E}_2 - \frac{m_1 \tau_2 - \omega \tau_1}{m_1 m_2 - \omega^2}$. Note that the regulator needs to choose the taxes τ_1 and τ_2 on the two pollutants, which will uniquely determine X_1 and X_2 , the expectations of the flows of pollution. Alternatively, the regulator can be regarded to levy tax on both pollutants by choosing X_1 and X_2 . In Appendix A.2, we obtain the regulator's value function under taxes for both pollutants:

$$V(S_1, S_2, TT) = \alpha^{TT} + \beta_1 S_1 + \beta_2 S_2 + (\varphi_1/2)[S_1]^2 + (\varphi_2/2)[S_2]^2 + \gamma S_1 S_2 \quad (9)$$

where β_i , φ_i , and γ are as in (6) and α^{TT} has the following relationship with the intercept of the value function under quotas:

$$\alpha^{TT} = \alpha^{QQ} + \frac{\sigma^2}{1-\delta} [M + \delta \Omega] \quad (10)$$

where we have:

$$M = \frac{m_1(m_2 - \omega)^2 + m_2(m_1 - \omega)^2 - 2(m_1 m_2 - \omega^2)(m_1 + m_2 - 2\omega) + 2\omega(m_2 - \omega)(m_1 - \omega)}{2(m_1 m_2 - \omega^2)^2} \quad (11)$$

$$\Omega = \frac{\varphi_1(m_2 - \omega)^2 + \varphi_2(m_1 - \omega)^2 + 2\gamma(m_2 - \omega)(m_1 - \omega)}{2(m_1 m_2 - \omega^2)^2} \quad (12)$$

3.2.3. Mixed policy instruments

The regulator implements a quota on one pollutant and a tax on the other one, e.g., a tax on pollutant 1 and a quota on pollutant 2. Since quotas are always binding, the firm chooses the emissions for pollutant 1 given the quota on pollutant 2. That is, in each period, the representative firm chooses the emissions for pollutant 1 (E_1) by solving the optimization problem: $\min C(E_1, E_2, \theta) + \tau_1 E_1$, taking E_2 as given. First order condition yields: $E_1 = Y_1 + \frac{\theta}{m_1}$, where $Y_1 = \bar{E}_1 + \frac{\omega(\bar{E}_2 - E_2) - \tau_1}{m_1}$ is the expectation of the flow of pollutant 1. In Appendix A.3, we show the value function in this case is

$$V(S_1, S_2, TQ) = \alpha^{TQ} + \beta_1 S_1 + \beta_2 S_2 + (\varphi_1/2)[S_1]^2 + (\varphi_2/2)[S_2]^2 + \gamma S_1 S_2 \quad (13)$$

where β_i , φ_i , and γ are as in (6) and α^{TQ} can be expressed as:

$$\alpha^{TQ} = \alpha^{QQ} + \frac{\sigma^2}{2(1-\delta)m_1^2} [\delta \varphi_1 - m_1] \quad (14)$$

Similarly, it is not difficult to find the value function under the mixed policy which establishes a quota on pollutant 1 and a tax on pollutant 2 as:

$$V(S_1, S_2, QT) = \alpha^{QT} + \beta_1 S_1 + \beta_2 S_2 + (\varphi_1/2)[S_1]^2 + (\varphi_2/2)[S_2]^2 + \gamma S_1 S_2 \quad (15)$$

where we have:

$$\alpha^{QT} = \alpha^{QQ} + \frac{\sigma^2}{2(1-\delta)m_2^2} [\delta \varphi_2 - m_2] \quad (16)$$

Therefore, the coefficients of the value functions under different policy instruments differ in the intercepts only and their relations are described in (10), (14) and (16). It should be emphasized that these value functions represent the minimized expected total social costs under different policy combinations and they are crucial to the policy comparisons in the dynamic framework.

4. Initialization of the model

In this section, we provide the calibration of the dynamic model developed above to the global warming issue. We take into account that two of the most important GHGs, CO₂ and methane can interact with each other in environmental damages and may have (dis) economies of scope in joint abatement. By calibrating our model of multiple stock pollutants, we try to provide more insights into the choice of policy

instruments for climate change mitigation. The calibration of our model is essentially based on Moslener and Requate [33], where their focus is on the optimal (open-loop) abatement strategies for multiple GHGs (CO₂ and methane) rather than the choice of policy instruments. As there is no asymmetric information in their analysis, there should be no difference between the usage of taxes and quotas in their case.

Note that there are significant differences in the two GHGs. For instance, CO₂ stays in the atmosphere for a much longer time than methane, which implies a larger decay rate for methane. Let us denote CO₂ as pollutant 1 and methane as pollutant 2. Following Moslener and Requate [33] and Hoel and Karp [14], we choose the decay rates for the two pollutants as $\rho_1 = 0.005$ for CO₂ and $\rho_2 = 0.1$ for methane, respectively. It implies a half-life time of 139 years for CO₂ and 7 years for methane, which reflects a much longer stay of CO₂ in the atmosphere. The discount factor δ is chosen as 0.98.⁴

Regarding the environmental damages, Moslener and Requate [33] used a damage function of the form:

$$D^{MR}(S_1, S_2) = d_1^{MR}(\alpha_1^{MR} S_1 + \alpha_2^{MR} S_2) + d_2^{MR}(\alpha_1^{MR} S_1 + \alpha_2^{MR} S_2)^2 \quad (17)$$

They estimated the parameters as: $\alpha_1^{MR} = 1$, $\alpha_2^{MR} = 60$, $d_1^{MR} = -0.352$ and $d_2^{MR} = 4 \cdot 10^{-13}$. By comparing the coefficients of their damage function (i.e., Eq. (17) above) with those in our damage function (i.e., Eq. (3)) and keeping them consistent, we can set the parameter in our damage function as: $d_1 = d_1^{MR} \alpha_1^{MR} = -0.352$, $d_2 = d_1^{MR} \alpha_2^{MR} = -21.12$, $\epsilon_1 = 2d_2^{MR}(\alpha_1^{MR})^2 = 8 \cdot 10^{-13}$, $\epsilon_2 = 2d_2^{MR}(\alpha_2^{MR})^2$, and $\varpi = \frac{2.88 \times 10^{-9}}{2d_2^{MR} \alpha_1^{MR} \alpha_2^{MR}} = 4.8 \times 10^{-11}$.⁵

As for the abatement costs, Moslener and Requate [33] employ a cost function in the following form for both CO₂ and methane:

$$C_{gas}^{MR}(E_{gas}) = \sum_{i=1}^4 \frac{c_i^{gas} (\bar{E}_{gas} - E_{gas})^i}{i} \quad (18)$$

where the parameters are set as in Table 1. The separate abatement cost for the two GHGs implies no (dis) economies of scope for firms in the joint abatement process, which follows with $\omega = 0$.

We choose the parameters for our quadratic abatement cost function, m_1 (CO₂) and m_2 (methane), in such a way that the expected respective abatement costs of pollutants 1 and 2 best fit the abatement cost in Moslener and Requate [33] by setting the same laissez-faire emission levels. It leads to the estimates $m_1 = 1.23 \times 10^{-8}$ and $m_2 = 4.77 \times 10^{-5}$.⁶ The parameter settings of our calibration for the baseline case are summarized in Table 2.

5. Results and discussions

5.1. Baseline results

Though the value of the variance σ^2 for the asymmetric information in abatement cost (θ) is unknown, we can still compare the value functions (the minimized expected social costs) under different policy instruments through the comparison of Eqs. (10), (14) and (16). Plugging the parameters from Table 2, one can numerically solve the coefficients of the value functions based on (8.1)–(8.6), (10), (14) and

⁴ The choice of discount rate is critical to climate policy assessments. Most of the studies on climate policy design use a discount rate between 1% and 5%. For instance, the Stern Review on the Economics of Climate Change (2007) employs a discount rate of 1.4%, while the discount rate used in Hoel and Karp [14] is 3% and that used in Newell and Pizer [15] and Karp and Zhang [4] is 5%. Therefore, in our paper, we choose the discount factor of 0.98 (a discount rate of 2%), which lies between the Stern Review and Hoel and Karp [14] as a baseline case. In the sensitivity analysis below, we set the discount factor to 0.95 (a discount rate of about 5%), which is consistent with Newell and Pizer [15], Karp and Zhang [4].

⁵ These parameters implies weak convexity of the damage function; see Footnote ².

⁶ Specifically, we used the ordinary least squares (OLS) method to estimate the parameters, in order that our abatement cost best fits that in Moslener and Requate [33]. The detailed procedure for estimating m_1 and m_2 is available from the author upon request.

Table 1
Parameters for abatement costs in Moslener and Requate [33].

| | \bar{E}_{gas} | c_1^{gas} | c_2^{gas} | c_3^{gas} | c_4^{gas} |
|-----------------|----------------------|-------------|----------------------|------------------------|-----------------------|
| CO ₂ | $3.00 \cdot 10^{10}$ | −3.483 | $6.08 \cdot 10^{-9}$ | $-5.72 \cdot 10^{-19}$ | $4.96 \cdot 10^{-29}$ |
| Methane | $1.12 \cdot 10^8$ | −0.832 | $7.87 \cdot 10^{-6}$ | $-6.20 \cdot 10^{-13}$ | $1.74 \cdot 10^{-20}$ |

Table 2
Calibration of the model for a baseline case.

| Parameters | Values | Parameters | Values |
|-------------|----------------------|-------------|----------------------|
| d_1 | −0.352 | d_2 | −21.12 |
| e_1 | $8 \cdot 10^{-13}$ | e_2 | $2.88 \cdot 10^{-9}$ |
| \bar{E}_1 | $3.00 \cdot 10^{10}$ | \bar{E}_2 | $1.12 \cdot 10^8$ |
| m_1 | $1.23 \cdot 10^{-8}$ | m_2 | $4.77 \cdot 10^{-5}$ |
| ω | 0 | ϖ | $4.8 \cdot 10^{-11}$ |
| ρ_1 | 0.005 | ρ_2 | 0.1 |
| δ | 0.98 | | |

Table 3
Comparisons of policy instruments for GHGs for the baseline case.

| Policies | Constant terms for value functions |
|--|---|
| Quotas on both CO ₂ and methane (QQ) | $\alpha^{QQ} = 2.2869 \times 10^{13}$ |
| Taxes on both CO ₂ and methane (TT) | $\alpha^{TT} = \alpha^{QQ} - 2.02894 \times 10^9 \times \sigma^2$ |
| A tax on CO ₂ and a quota on methane (TQ) | $\alpha^{TQ} = \alpha^{QQ} - 2.02845 \times 10^9 \times \sigma^2$ |
| A quota on CO ₂ and a tax on methane (QT) | $\alpha^{QT} = \alpha^{QQ} - 5.23959 \times 10^5 \times \sigma^2$ |

(16). Consequently, the constant terms of the value functions under different policy options are obtained as in Table 3, and other coefficients of the value functions are solved the same for all policy options: $\gamma = 3.85813 \times 10^{-10}$, $\varphi_1 = 2.51378 \times 10^{-11}$, $\varphi_2 = 1.39062 \times 10^{-8}$, β_1 ,

$$= 15.8167, \beta_2 = -84.4641$$

Table 3 shows that the optimal policy under the joint consideration of two most important GHGs would be to tax both CO₂ and methane, which occurs with the lowest social cost. Regarding the mixed policies, implementing a tax on CO₂ along with a quota on methane (TQ) is superior than the opposite way, with a quota on CO₂ and a tax on methane. Among the four policy combinations, establishing the quota system for both pollutants is the least desirable option with a highest total cost.

5.2. Sensitivity analysis

5.2.1. The effect of (dis) economies of scope in joint abatement

In the baseline results above, we assume no effect of (dis) economies of scope in the joint abatement of CO₂ and methane by setting the parameter $\omega = 0$. In practice, CO₂ and methane could be substitutive or complementary at different occasions. For instance, waste treatment where combustion on the one hand, and disposition of waste, on the other hand, causes either CO₂ or methane emissions respectively, which makes the two GHGs substitutes [32]. Meanwhile, when we try to reduce the mining (and thus the usage) of coal, the emissions of both methane and CO₂ will be reduced, implying the complementarity of the two GHGs ($\omega < 0$). Therefore, in this section, we investigate the effect of the (dis) economies of scope in the joint abatement of the two GHGs on the optimal policy choices.

Table 4 shows the results when CO₂ and methane are substitutes, i.e., there is diseconomies of scope in the joint abatement. When the parameter ω is changed from 0 to $2 \cdot 10^{-7}$ or $5 \cdot 10^{-7}$, the ranking of the policy options remains the same. That is, taxing both CO₂ and methane remains the best policy option and the policy that implements a tax on CO₂ and a quota on methane ranks the second. It can also be seen that

Table 4
Comparisons of policy instruments when CO₂ and methane are substitutes.

| Policies | Constant terms for value functions ($\omega = 2 \cdot 10^{-7}$) | Constant terms for value functions ($\omega = 5 \cdot 10^{-7}$) |
|----------|--|--|
| QQ | $\alpha^{QQ} = 9.52923 \times 10^{11}$ | $\alpha^{QQ} = 2.11175 \times 10^{13}$ |
| TT | $\alpha^{TT} = \alpha^{QQ} - 2.15936 \times 10^9 \times \sigma^2$ | $\alpha^{TT} = \alpha^{QQ} - 3.45946 \times 10^9 \times \sigma^2$ |
| TQ | $\alpha^{TQ} = \alpha^{QQ} - 2.02844 \times 10^9 \times \sigma^2$ | $\alpha^{TQ} = \alpha^{QQ} - 2.02850 \times 10^9 \times \sigma^2$ |
| QT | $\alpha^{QT} = \alpha^{QQ} - 5.23959 \times 10^5 \times \sigma^2$ | $\alpha^{QT} = \alpha^{QQ} - 5.23959 \times 10^5 \times \sigma^2$ |

the larger the diseconomies of scope in joint abatement (i.e., a larger value of ω), the higher the total expected cost in general. For instance, the cost under the QQ policy (quotas for both GHGs) when $\omega = 5 \cdot 10^{-7}$ is substantially higher than the cost with $\omega = 2 \cdot 10^{-7}$. Meanwhile, the relative advantage of TT policy (taxing both GHGs) over the second-ranked TQ policy (a tax on CO₂ and a quota on methane) becomes larger with a larger value of ω , due to larger diseconomies of scope in abatement.

As mentioned earlier, CO₂ and methane can also be complements. Accordingly, we investigate the choice of policy options under economies of scope in the joint abatement with $\omega < 0$. The results are shown in Table 5, where the ranking of policy options does not change with different magnitude of complementarity in joint abatement. In summary, the conclusion of the TT (taxing both) policy being ranked first among the four policy combinations is rather robust with respect to the (dis) economies of scope in the joint abatement of CO₂ and methane.

5.2.2. The effect of different discount rate

Discounting has been shown its importance and sensitivity in climate policy design. For instance, a number of previous studies (e.g., [16,14,4]) show that an increase in the discount rate favors the usage of taxes for CO₂. In this section, we investigate the effect of a higher (lower) discount rate on the choice of policy instruments. We change the discount factor (δ) from 0.98 in the baseline case to 0.95 [15,4], which implies a continuous discount rate of 5% approximately. From the results in Table 6, the TT policy is still the best policy option for the abatement of the two GHGs even with a higher discount rate. The result also holds combining with different magnitude of (dis) economies of scope in joint abatement. The analysis with a lower discount factor of 0.9 was also conducted, which supports the above conclusions and is omitted here.

It can be seen from the sensitivity analysis that the ranking of the policy options are stable with respect to different values of (dis) economies of scope in emission abatement and the discounting rate. That is, it is optimal for the policy-makers to tax both CO₂ and methane with the joint consideration of these two GHGs. For the rest of the policy combinations, the mixed policy with a tax on CO₂ and a quota on methane is preferable, while setting quotas for both pollutants always ranks the last.

6. Conclusions and policy implications

This paper investigates the optimal policy instruments for climate change mitigation under the joint consideration of CO₂ and methane.

Table 5
Comparisons of policy instruments when CO₂ and methane are complements.

| Policies | Constant terms for value functions ($\omega = -2 \cdot 10^{-7}$) | Constant terms for value functions ($\omega = -5 \cdot 10^{-7}$) |
|----------|---|---|
| QQ | $\alpha^{QQ} = 2.22021 \times 10^{13}$ | $\alpha^{QQ} = 1.88713 \times 10^{13}$ |
| TT | $\alpha^{TT} = \alpha^{QQ} - 2.19472 \times 10^9 \times \sigma^2$ | $\alpha^{TT} = \alpha^{QQ} - 3.60021 \times 10^9 \times \sigma^2$ |
| TQ | $\alpha^{TQ} = \alpha^{QQ} - 2.02850 \times 10^9 \times \sigma^2$ | $\alpha^{TQ} = \alpha^{QQ} - 2.02872 \times 10^9 \times \sigma^2$ |
| QT | $\alpha^{QT} = \alpha^{QQ} - 5.23959 \times 10^5 \times \sigma^2$ | $\alpha^{QT} = \alpha^{QQ} - 5.23960 \times 10^5 \times \sigma^2$ |

Table 6
Comparisons of policy instruments for GHGs.

| Policies | Constant terms ($\delta = 0.95, \omega = 0$) | Constant terms ($\delta = 0.95, \omega = -5 \cdot 10^{-7}$) | Constant terms ($\delta = 0.95, \omega = 5 \cdot 10^{-7}$) |
|----------|---|---|---|
| QQ | $\alpha^{QQ} = 5.36937 \times 10^{11}$ | $\alpha^{QQ} = 4.36452 \times 10^{11}$ | $\alpha^{QQ} = 5.18566 \times 10^{11}$ |
| TT | $\alpha^{TT} = \alpha^{QQ} - 8.12378 \times 10^8 \times \sigma^2$ | $\alpha^{TT} = \alpha^{QQ} - 1.44263 \times 10^9 \times \sigma^2$ | $\alpha^{TT} = \alpha^{QQ} - 1.38583 \times 10^9 \times \sigma^2$ |
| TQ | $\alpha^{TQ} = \alpha^{QQ} - 8.12179 \times 10^8 \times \sigma^2$ | $\alpha^{TQ} = \alpha^{QQ} - 8.122 \times 10^8 \times \sigma^2$ | $\alpha^{TQ} = \alpha^{QQ} - 8.12179 \times 10^8 \times \sigma^2$ |
| QT | $\alpha^{QT} = \alpha^{QQ} - 2.09592 \times 10^5 \times \sigma^2$ | $\alpha^{QT} = \alpha^{QQ} - 2.09592 \times 10^5 \times \sigma^2$ | $\alpha^{QT} = \alpha^{QQ} - 2.09592 \times 10^5 \times \sigma^2$ |

We develop a dynamic model for multiple stock pollutants and calibrate it to the global warming issue. The result suggests that the policy taxing both CO₂ and methane dominates the other policy options. We also find that a mixed policy with a tax levied on CO₂ and a quota on methane ranks the second.

Consistent with the literature on one pollutant (e.g., [16,14]) which finds that taxing CO₂ is optimal, our results show that even with the consideration of methane and its interactions with CO₂, applying tax on CO₂ is still preferable than the quota system. It is also optimal for the policy-makers to tax methane with the joint consideration of CO₂. In the real world, the implementation of taxes on CO₂ and methane would bring revenue to the government and therefore might be preferable from this perspective. However, it should be clear that the goal of carbon taxes is not to maximize tax revenue, but to reduce carbon emissions over time. In this respect, Denmark's experience with carbon taxes could be instructive: to tax the industrial emissions of carbon and return the revenue to industry through subsidies for research and investment in alternative energy sources. Approximately 40% of Danish carbon tax revenue is used for environmental subsidies, while the other 60% is returned to the industry. In this way, the tax revenue, which invests in energy substitutes, is locked away from policy-makers. Eventually, the carbon tax leads to less pollution rather than to more revenue. This would make the adoption of carbon taxes more effective in the reduction of GHG emissions.

Admittedly, there are several other concerns in the price-versus-quantity comparisons in practice. For instance, the enforceability of price-based regulations is lower than of quantity instruments [24], and the command and control type of regulations are still the predominant instruments worldwide [36]. In case that taxing methane is not politically feasible or the merits of quotas in enforcement are taken into consideration, establishing a methane emissions trading system in addition to the tax policy on carbon dioxide is also desirable. Actually, there has been discussions on whether methane emissions trading is a viable option in practice [37]. Given the diverse and diffuse nature of methane sources, policies targeting the mitigation of methane emissions tend to be constrained within individual sectors (e.g. waste, agriculture, coal mines). In that case, methane emissions trading might offer the possibility of a consolidated approach that could be applied across all sectors.

Mitigating climate change involves multiple pollutants. However, both in theory and practice more spotlights are focused on carbon

dioxide only. Though environmental regulations targeting other GHGs are recently addressed, for instance the Strategy to Reduce Methane Emission Plan introduced in the United States in 2015, ignoring the interactive effects between pollutants and developing policies independently either reinforces or constrains the other policy [38], which may bias the long-term goal of environmental regulations. Therefore, multiple GHGs, as well as their correlations and accumulative nature, should be considered in an integrated and systematic way in future policy makings of global climate change mitigation.

It is not an easy exercise to conduct the tax-versus-quota analysis for multiple GHGs in a dynamic framework. For the sake of simplicity and in the interest of grasping the essence of the problem, a number of assumptions have been made. For instance, inspired by Smith et al. [39], only CO₂ and methane are taken into account in this study. In fact, several other greenhouse gases such as nitrous oxide and the chloro-fluorocarbons also contribute to global warming (though with less impact). This can be a direction for further research by considering more state variables in the dynamic model. In addition, note that the results obtained in this paper should not be interpreted the same across industries. The correlation between carbon dioxide and methane in the joint production or joint abatement process differs from one industry to another. For future research, with credible data on the damage, abatement cost parameters and stocks of both pollutants for a specific industry, it would be interesting to perform a case study and derive the optimal industry-specific policy. Moreover, accounting for both the climate change and air pollution issues (and their interactions) would be of greater significance for policy makings at the country/province/city level. By building and calibrating a similar model with one greenhouse gas (e.g., CO₂) and one local pollutant (e.g. PM_{2.5} or SO₂), the research on the optimal joint policy of climate change and air pollution may be promising in future studies.

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Appendix A. Technical details

A.1. The value function $V(S_1, S_2, QQ)$

Since the pollution emissions (E_i) and stocks (S_i) are deterministic under the quota regime, we can rewrite the regulator's dynamic programming Eq. (5) as (ignoring the time notation for convenience):

$$V(S_1, S_2, QQ) = \min_{\{E_1, E_2\}} \left\{ \frac{m_1}{2} (\bar{E}_1 - E_1)^2 + \frac{m_2}{2} (\bar{E}_2 - E_2)^2 + \omega (\bar{E} - E_1)(\bar{E} - E_2) + d_1 S_1 + d_2 S_2 + \frac{\varepsilon_1}{2} [S_1]^2 + \frac{\varepsilon_2}{2} [S_2]^2 + \varpi S_1 S_2 + \delta V[(1-\rho_1)S_1 + E_1, (1-\rho_2)S_2 + E_2, QQ] \right\} \quad (A.1)$$

where we make use of the fact that $E(\theta(t)) = 0$. Because of the linear-quadratic control problem, the value function is quadratic:

$$V(S_1, S_2, QQ) = \alpha + \beta_1 S_1 + \beta_2 S_2 + (\varphi_1/2)[S_1]^2 + (\varphi_2/2)[S_2]^2 + \gamma S_1 S_2 \quad (A.2)$$

where α , β_i , φ_i , and γ are coefficients to be determined. Plugging (A.2) into (A.1) and performing the minimization, one can obtain the first-order conditions:

$$m_1(\bar{E}_1 - E_1) + \omega(\bar{E}_2 - E_2) = \delta\{\beta_1 + \varphi_1[(1-\rho_1)S_1 + E_1] + \gamma[(1-\rho_2)S_2 + E_2]\} \quad (\text{A.3.1})$$

$$m_2(\bar{E}_2 - E_2) + \omega(\bar{E}_1 - E_1) = \delta\{\beta_2 + \varphi_2[(1-\rho_2)S_2 + E_2] + \gamma[(1-\rho_1)S_1 + E_1]\} \quad (\text{A.3.2})$$

from which we can obtain the optimal control rules:

$$E_1 = \frac{(m_2 + \delta\varphi_2)(\bar{E}_1 m_1 + \bar{E}_2 \omega - \delta\beta_1) - (\omega + \delta\gamma)(\bar{E}_2 m_2 + \bar{E}_1 \omega - \delta\beta_2)}{(m_1 + \delta\varphi_1)(m_2 + \delta\varphi_2) - (\omega + \delta\gamma)^2} - \frac{\delta(1-\rho_1)[(\varphi_1 m_2 - \gamma\omega) + \delta(\varphi_1 \varphi_2 - \gamma^2)]}{(m_1 + \delta\varphi_1)(m_2 + \delta\varphi_2) - (\omega + \delta\gamma)^2} S_1 - \frac{\delta(1-\rho_2)(\gamma m_2 - \varphi_2 \omega)}{(m_1 + \delta\varphi_1)(m_2 + \delta\varphi_2) - (\omega + \delta\gamma)^2} S_2 \quad (\text{A.4.1})$$

$$E_2 = \frac{(m_1 + \delta\varphi_1)(\bar{E}_2 m_2 + \bar{E}_1 \omega - \delta\beta_2) - (\omega + \delta\gamma)(\bar{E}_1 m_1 + \bar{E}_2 \omega - \delta\beta_1)}{(m_1 + \delta\varphi_1)(m_2 + \delta\varphi_2) - (\omega + \delta\gamma)^2} - \frac{\delta(1-\rho_2)[(\varphi_2 m_1 - \gamma\omega) + \delta(\varphi_1 \varphi_2 - \gamma^2)]}{(m_1 + \delta\varphi_1)(m_2 + \delta\varphi_2) - (\omega + \delta\gamma)^2} S_2 - \frac{\delta(1-\rho_1)(\gamma m_1 - \varphi_1 \omega)}{(m_1 + \delta\varphi_1)(m_2 + \delta\varphi_2) - (\omega + \delta\gamma)^2} S_1 \quad (\text{A.4.2})$$

For the sake of convenience, let us denote (A.4.1) and (A.4.2) as:

$$E_1 = \kappa_1 - \eta_1 S_1 - \mu_1 S_2 \quad (\text{A.5.1})$$

$$E_2 = \kappa_2 - \eta_2 S_2 - \mu_2 S_1 \quad (\text{A.5.2})$$

where the expressions of κ_i , η_i and μ_i ($i = 1, 2$) can be found in (A.4.1) and (A.4.2). It can be seen that κ_i , η_i and μ_i are functions of model parameters and coefficients of the value function $V(S_1, S_2, QQ)$. Substituting (A.5.1) and (A.5.2) and (Appendix A.2) into (Appendix A.1) to eliminate the minimization, one can get a quadratic equation in the state variables (S_1, S_2). Equating the coefficients of $S_1 S_2, S_1^2, S_2^2$ ($i = 1, 2$) and 1 on both sides gives the equations for $\gamma, \varphi_i, \beta_i$ and α in the text (i.e., (8.1)–(8.6)).⁷

A.2. The value function $V(S_1, S_2, TT)$

Different from the quota regime, the emissions of pollution are stochastic under the tax regime. As stated in Section 3.2, we can think of the regulator under the tax regime as choosing the expectations of the flows of pollution, X_1 and X_2 . Then the actual flows of pollution emitted by the firm would be $E_1 = X_1 + \frac{(m_2 - \omega)\theta}{m_1 m_2 - \omega^2}$ and $E_2 = X_2 + \frac{(m_1 - \omega)\theta}{m_1 m_2 - \omega^2}$, which are stochastic to the regulator. The regulator's problem (5) can be written as follows under taxes for both pollutants:

$$V[S_1(t), S_2(t), TT] = \min_{\{X_1(t), X_2(t)\}} \mathbb{E}_{\theta(t)} \left\{ C(X_1(t) + \frac{(m_2 - \omega)\theta(t)}{m_1 m_2 - \omega^2}, X_2(t) + \frac{(m_1 - \omega)\theta(t)}{m_1 m_2 - \omega^2}, \theta(t)) + D(S_1(t), S_2(t)) \right. \\ \left. + \delta V[(1-\rho_1)S_1(t) + X_1(t) + \frac{(m_2 - \omega)\theta(t)}{m_1 m_2 - \omega^2}, (1-\rho_2)S_2(t) + X_2(t) + \frac{(m_1 - \omega)\theta(t)}{m_1 m_2 - \omega^2}, TT] \right\} \quad (\text{A.6})$$

Making use of the facts that $\mathbb{E}(\theta(t)) = 0$ and $\mathbb{E}([\theta(t)]^2) = \sigma^2$, and taking the expectation with respect to $\theta(t)$, the abatement cost under the tax policy ($X_1(t), X_2(t)$) can be obtained (after some calculations) as:

$$\mathbb{E} \left[C \left(X_1(t) + \frac{(m_2 - \omega)\theta(t)}{m_1 m_2 - \omega^2}, X_2(t) + \frac{(m_1 - \omega)\theta(t)}{m_1 m_2 - \omega^2}, \theta(t) \right) \right] = \frac{m_1}{2} [\bar{E}_1 - X_1(t)]^2 + \frac{m_2}{2} [\bar{E}_2 - X_2(t)]^2 + \omega [\bar{E}_1 - X_1(t)][\bar{E}_2 - X_2(t)] + M \cdot \sigma^2 \quad (\text{A.7})$$

where

$$M = \frac{m_1(m_2 - \omega)^2 + m_2(m_1 - \omega)^2 - 2(m_1 m_2 - \omega^2)(m_1 + m_2 - 2\omega)}{2(m_1 m_2 - \omega^2)^2} \quad (\text{A.8})$$

Denoting the value function in this case as:

$$V(S_1, S_2, TT) = \alpha^{TT} + \beta_1^{TT} S_1 + \beta_2^{TT} S_2 + (\varphi_1^{TT}/2)[S_1]^2 + (\varphi_2^{TT}/2)[S_2]^2 + \gamma^{TT} S_1 S_2 \quad (\text{A.9})$$

where α^{TT} , β_i^{TT} , φ_i^{TT} , and γ^{TT} are coefficients to be determined. Making use of (A.9) and after some tedious but straightforward calculations, we have:

$$\mathbb{E} \left\{ V \left[(1-\rho_1)S_1 + X_1 + \frac{(m_2 - \omega)\theta}{m_1 m_2 - \omega^2}, (1-\rho_2)S_2 + X_2 + \frac{(m_1 - \omega)\theta}{m_1 m_2 - \omega^2}, TT \right] \right\} = V[(1-\rho_1)S_1 + X_1, (1-\rho_2)S_2 + X_2, TT] + \Omega \cdot \sigma^2 \quad (\text{A.10})$$

where we have:

$$\Omega = \frac{\varphi_1^{TT}(m_2 - \omega)^2 + \varphi_2^{TT}(m_1 - \omega)^2 + 2\gamma^{TT}(m_2 - \omega)(m_1 - \omega)}{2(m_1 m_2 - \omega^2)^2} \quad (\text{A.11})$$

Being aware of (A.7) and (A.10), we can rewrite the regulator's problem (A.6) as:

⁷ The complete calculations are available from the author upon requests.

$$V(S_1, S_2, TT) = \min_{\{X_1, X_2\}} \left\{ \frac{m_1}{2} (\bar{E}_1 - X_1)^2 + \frac{m_2}{2} (\bar{E}_2 - X_2)^2 + \omega (\bar{E}_1 - X_1)(\bar{E}_2 - X_2) + M \cdot \sigma^2 + d_1 S_1 + d_2 S_2 + \frac{\xi_1}{2} [S_1]^2 + \frac{\xi_2}{2} [S_2]^2 + \varpi S_1 S_2 + \delta \{V[(1-\rho_1)S_1 + X_1, (1-\rho_2)S_2 + X_2, TT] + \Omega \cdot \sigma^2\} \right\} \quad (\text{A.12})$$

Comparing (A.12) and (A.1), one can conclude that the value function $V(S_1, S_2, TT)$ should be identical to the value function $V(S_1, S_2, QQ)$ except for the intercept. Therefore, for convenience we write:

$$V(S_1, S_2, TT) = \alpha^{TT} + \beta_1 S_1 + \beta_2 S_2 + (\varphi_1/2)[S_1]^2 + (\varphi_2/2)[S_2]^2 + \gamma S_1 S_2 \quad (\text{A.13})$$

which is reproduced as (9) in the text. And (A.11) is therefore reproduced as (12) in the text. Substituting (A.13) into (A.12), the first order conditions for the minimization in (A.12) yield:

$$X_1 = \kappa_1 - \eta_1 S_1 - \mu_1 S_2 \quad (\text{A.14.1})$$

$$X_2 = \kappa_2 - \eta_2 S_2 - \mu_2 S_1 \quad (\text{A.14.2})$$

where κ_i , η_i and μ_i are found as exactly in (A.5.1) and (A.5.2). This implies that the expected emissions under taxes are the same as the emissions under quotas, which is reflective of the Principle of Certainty Equivalence. Following a similar procedure as in Appendix A1 above, one can obtain a similar system of equations for the coefficients of the value function $V(S_1, S_2, TT)$. As can be expected, the equations regarding γ , φ_i , and β_i are the same as (8.1)–(8.5) and we need to present the equation regarding the intercept α^T only:

$$\alpha^{TT} = \frac{m_1}{2} (\bar{E}_1 - \kappa_1)^2 + \frac{m_2}{2} (\bar{E}_2 - \kappa_2)^2 + \omega (\bar{E}_1 - \kappa_1)(\bar{E}_2 - \kappa_2) + M \cdot \sigma^2 + \delta \left\{ \alpha^{TT} + \beta_1 \kappa_1 + \beta_2 \kappa_2 + \frac{\varphi_1}{2} (\kappa_1)^2 + \frac{\varphi_2}{2} (\kappa_2)^2 + \gamma \kappa_1 \kappa_2 + \Omega \cdot \sigma^2 \right\} \quad (\text{A.15.1})$$

Comparing Eq. (A.15.1) with Eq. (8.6) in the text, we have:

$$\alpha^{TT} = \alpha + \frac{\sigma^2}{1-\delta} [M + \delta \Omega] \quad (\text{A.15.2})$$

which is reproduced as Eq. (10) in the main text.

A.3. The value function $V(S_1, S_2, TQ)$

As shown in Section 3.2, with a tax on pollutant 1 and a quota on pollutant 2, the emissions for pollutant 1 would be: $E_1 = Y_1 + \frac{\theta}{m_1}$, where $Y_1 = \bar{E}_1 + \frac{\omega(\bar{E}_2 - E_2) - \tau_1}{m_1}$. In this case, we can think of the regulator as choosing the expected emissions for pollutant 1 (Y_1) and actual emissions (quotas) of pollutant 2 (E_2). The regulator's dynamic programming Eq. (5) can be written as follows in this case:

$$V[S_1(t), S_2(t), TQ] = \min_{\{Y_1(t), E_2(t)\}} \mathbb{E}_{\theta(t)} \left\{ C(Y_1(t) + \frac{\theta(t)}{m_1}, E_2(t), \theta(t)) + D(S_1(t), S_2(t)) + \delta V[(1-\rho_1)S_1(t) + Y_1(t) + \frac{\theta(t)}{m_1}, (1-\rho_2)S_2(t) + E_2(t), TQ] \right\} \quad (\text{A.16})$$

The procedure to derive the coefficients of the value functions under this mixed policy is almost the same as that under pure tax policies (see Appendix A2). The differences lie in the calculations of expectations only. Specifically, under this mixed policy we have:

$$\mathbb{E} \left[C \left(Y_1(t) + \frac{\theta(t)}{m_1}, E_2(t), \theta(t) \right) \right] = \frac{m_1}{2} [\bar{E}_1 - Y_1(t)]^2 + \frac{m_2}{2} [\bar{E}_2 - \tilde{E}_2^\wedge(t)]^2 + \omega [\bar{E}_1 - Y_1(t)][\bar{E}_2 - \tilde{E}_2^\wedge(t)] - \frac{\sigma^2}{2m_1} \quad (\text{A.17})$$

$$\mathbb{E} \left\{ V \left[(1-\rho_1)S_1 + Y_1 + \frac{\theta}{m_1}, (1-\rho_2)S_2 + E_2, TQ \right] \right\} = V[(1-\rho_1)S_1 + Y_1, (1-\rho_2)S_2 + E_2, TQ] + \frac{\varphi_1 \sigma^2}{2m_1^2} \quad (\text{A.18})$$

Accordingly, the value function is found to be:

$$V(S_1, S_2, TQ) = \alpha^{TQ} + \beta_1 S_1 + \beta_2 S_2 + (\varphi_1/2)[S_1]^2 + (\varphi_2/2)[S_2]^2 + \gamma S_1 S_2$$

where β_i , φ_i , and γ are also same as those in the value functions $V(S_1, S_2, QQ)$ and

$$\alpha^{TQ} = \alpha^{QQ} + \frac{\sigma^2}{2(1-\delta)m_1^2} [\delta \varphi_1 - m_1]$$

which is Eq. (14) in the text.

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